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HEADPHONE SYSTEM

BACKGROUND OF THE INVENTION

1. FIELD OF THE INVENTION:

The present invention relates to a headphone system for reproducing a multi-channel acoustic signal.

2. DESCRIPTION OF THE RELATED ART:

Recently, as multi-media systems such as DVD systems have become commonplace, more and more multi-channel acoustic information has been provided together with video.

Conventionally, systems for virtually reproducing a multi-channel acoustic signal using a headphone have been proposed.

For example, International Publication WO95/20866 discloses a technology for filtering signals which are input to right and left speakers, so as to cause a sound source provided in front of or behind the listener to be recognized or perceived by the listener.

Figure **19** shows a structure of a headphone system described in International Publication WO95/20866.

The headphone system shown in Figure **19** includes a right ear speaker **1901** and a left ear speaker **1902**. The speakers **1901** and **1902** are fixed at positions distanced from the listener. The headphone system further includes filters **1910** and **1911**. Reference numeral **1960** represents a virtual sound source located behind the listener.

In Figure **19**, H1 indicates a transfer function from the virtual sound source **1960** to the right ear of the listener.

H2 indicates a transfer function from the virtual sound source **1960** to the left ear of the listener. Transfer function H1 is set in the filter **1910**, and transfer function H2 is set in the filter **1911**.

An input signal Z is input to the filters **1910** and **1911**. The output from the filter **1910** is input to the right ear speaker **1901**, and the output from the filter **1911** is input to the left ear speaker **1902**.

Thus, the listener can recognize the virtual sound source **1960**.

It is relatively easy for a human being to correctly recognize the sound source to his/her right or left. The reason for this is that he/she has ears on the right side and the left side of the head. It is considered that a human being recognizes the sound source to his/her right or left based on a plurality of different types of information, including the time period required by the signal from the sound source to reach his/her left ear, the time period required by the signal from the sound source to reach his/her right ear, and the difference in the signal levels. Therefore, there is little difference among individuals in the ability to recognize or distinguish between a sound source to his/her right or left.

It is relatively difficult for a human being to correctly recognize or distinguish between a sound source in front of or behind him/her. The reason for this is that there is little difference between the time period required by the signal from the sound source to reach his/her right ear and the time period required by the signal from the sound

source to reach his/her left ear. It is considered that a human being recognizes or distinguishes between a sound source in front of or behind him/her based on a single piece of information of the absolute value of the frequency spectrum of the sound source. Since the head-related transfer function from the sound source to the ears is different among individuals due to each person's individual shape of the head, there is a relatively large difference among individuals in the ability to recognize a sound source located in front of or behind the listener.

Using the conventional technology shown in Figure **19**, the sound from a sound source located in front of or behind the listener is transferred to him/her by the combination of the right ear and left ear speakers **1901** and **1902** and the filter processing. Using such technology, it is difficult to cause the listener to correctly recognize a sound source located in front of or behind him/her, due to the individual difference in the transfer function. Especially for high frequencies, the difference between different individuals' recognition of front/rear sound direction is undesirably large, because the influence of differences between different individuals' transfer functions on such recognition is greater for high frequencies than it is for low frequencies.

SUMMARY OF THE INVENTION

A headphone system according to the present invention includes a headphone; and a signal processing circuit for outputting an acoustic signal to the headphone. The headphone includes a first speaker and a third speaker for a right ear of a listener, a second speaker and a fourth

speaker for a left ear of the listener, and a support for supporting the first through fourth speakers so that the first and second speakers are located forward with respect to a vertical plane including a straight line connecting the hole of the right ear and the hole of the left ear of the listener, the third and fourth speakers are located rearward with respect to the vertical plane, and the first through fourth speakers are out of contact with the right ear and the left ear of the listener.

In one embodiment of the invention, the signal processing circuit outputs an acoustic signal, for causing the listener to recognize a front sound source located forward with respect to the listener, to the first and second speakers.

In one embodiment of the invention, the signal processing circuit outputs an acoustic signal, for causing the listener to recognize a rear sound source located rearward with respect to the listener, to the third and fourth speakers.

In one embodiment of the invention, the signal processing circuit outputs, among acoustic signals for causing the listener to recognize a rear sound source, acoustic signals having a frequency of a prescribed frequency fi or lower to the first and second speakers, and outputs acoustic signals having a frequency of the prescribed frequency fi or higher to the third and fourth speakers.

In one embodiment of the invention, the signal processing circuit outputs, among acoustic signals for

causing the listener to recognize a front sound source, acoustic signals having a frequency of a prescribed frequency fi or higher to the first and second speakers, and outputs acoustic signals having a frequency of the prescribed frequency fi or lower to the third and fourth speakers.

In one embodiment of the invention, the first and second speakers are located rearward with respect to a vertical plane including a straight line connecting a right eye and a left eye of the listener.

In one embodiment of the invention, the third speaker is located so that an angle between a straight line straight ahead direction of the listener and a vertical line running through the center of a front surface of the third speaker is in the range of about 100 degrees to about 120 degrees, and the fourth speaker is located so that an angle between the straight line in the straight ahead direction of the listener and a vertical line running through the center of a front surface of the fourth speaker is in the range of about 100 degrees to about 120 degrees.

In one embodiment of the invention, the headphone further includes a low frequency-dedicated speaker for reproducing only audio signals in a low frequency band.

In one embodiment of the invention, the low frequency-dedicated speaker is located in the vicinity of a rear part of the head of the listener, when the headphone is worn.

In one embodiment of the invention, the low

frequency-dedicated speaker is located in the vicinity of the top of the head of the listener, when the headphone is worn.

In one embodiment of the invention, the headphone further includes a vibration unit for vibrating based on a dedicated low frequency band signal used for reproducing only audio signals in a low frequency band, and the vibration unit is supported so as to be in close contact with a temporal region of the head of the listener, when the headphone is worn.

In one embodiment of the invention, the support includes a first supporting member for supporting the first and third speakers and a second supporting member for supporting the second and fourth speakers. The third speaker and the first supporting member are connected through a first connecting portion so that the third speaker is rotatable about the first connecting portion. The fourth speaker and the second supporting member are connected through a second connecting portion so that the fourth speaker is rotatable about the second connecting portion.

In one embodiment of the invention, the headphone further includes a first reflection plate for reflecting sound radiating from the third speaker and a second reflection plate for reflecting sound radiating from the fourth speaker. The third speaker is located so that a surface of a diaphragm of the third speaker includes a straight line connecting the hole of the right ear of the listener and the center of the third speaker, and the sound radiating from the third speaker and reflected by the first reflection plate reaches the right ear of the listener. The

fourth speaker is located so that a surface of a diaphragm of the fourth speaker includes a straight line connecting the hole of the left ear of the listener and the center of the fourth speaker, and the sound radiating from the fourth speaker and reflected by the second reflection plate reaches the left ear of the listener.

Thus, the invention described herein makes possible the advantage of providing a headphone system for reproducing a multi-channel acoustic signal so that the listener can correctly recognize or perceive a virtual sound source in front of or behind the listener regardless of the individual difference in the recognizing ability.

These and other advantages of the present invention will become apparent to those skilled in the art upon reading and understanding the following detailed description with reference to the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

Figures **1A**, **1B** and **1C** are a top view, a front view and a side view of a headphone **201** according to a first example of the present invention;

Figure **2** is a block diagram of a headphone system **101** according to the first example of the present invention, illustrating a structure of a signal processing circuit **301a**;

Figure **3** is a block diagram of the headphone system **101** according to the first example of the present invention, illustrating a structure of a signal processing circuit

301b;

Figures 4A, 4B and 4C are a top view, a front view and a side view of a headphone 202 according to a second example of the present invention;

Figure 5 is a graph illustrating an example of the front transfer function and the rear transfer function regarding a specific listener;

Figure 6 is a graph illustrating an example of the individual difference in the head-related transfer function;

Figure 7 is a block diagram of a headphone system 202 according to the second example of the present invention, illustrating a structure of a signal processing circuit 302;

Figures 8A, 8B and 8C are a top view, a front view and a side view of a headphone 203 according to a third example of the present invention;

Figure 9 is a block diagram of a headphone system 103 according to the third example of the present invention, illustrating a structure of a signal processing circuit 303;

Figures 10A, 10B and 10C are a top view, a front view and a side view of a headphone 204 according to a fourth example of the present invention, showing a low frequency-dedicated speaker 7 provided in the vicinity of a rear part of the head of the listener;

Figures 11A, 11B and 11C are a top view, a front view

and a side view of the headphone **204** according to the fourth example of the present invention, showing the low frequency-dedicated speaker **7** provided in the vicinity of the top of the head of the listener;

Figures **12A**, **12B** and **12C** are a top view, a front view and a side view of the headphone **204** according to the fourth example of the present invention, showing the low frequency-dedicated speaker **7** provided in the vicinity of another rear part of the head of the listener;

Figures **13A** and **13B** are a top view and a front view of the headphone **204** including a support assisting member **21'** having an improved shape;

Figures **14A** and **14B** are a top view and a front view of the headphone **204** including a support assisting member **21"** having another improved shape;

Figures **15A**, **15B** and **15C** are a top view, a front view and a side view of a headphone **205** according to a fifth example of the present invention, including diaphragms **10** and **11**;

Figure **16** is a top view of a headphone **206** according to a sixth example of the present invention;

Figure **17** is a top view of another headphone **206'** according to the sixth example of the present invention;

Figures **18A**, **18B** and **18C** are a top view, a front view and a side view of a headphone **207** according to a seventh example of the present invention; and

Figure **19** shows a structure of a conventional head phone system.

DESCRIPTION OF THE EMBODIMENTS

Hereinafter, the present invention will be described by way of illustrative examples with reference to the accompanying drawings.

(Example 1)

A headphone system **101** according to a first example of the present invention will be described with reference to Figures **1A** through **3**.

The headphone system **101** includes a headphone **201** and a signal processing circuit for outputting an acoustic signal to the headphone **201**.

Figure **1A**, **1B** and **1C** show a structure of the headphone **201**. Figure **1A** is a top view, Figure **1B** is a front view, and Figure **1C** is a side view of the headphone **201**.

As shown in Figure **1A**, **1B** and **1C**, the headphone **201** includes right ear speakers **1** and **3**, left ear speakers **2** and **4**, and a support **8** for supporting the speakers **1** through **4**.

The support **8** includes, for example, a headphone band **20** and speaker supporting members **30** and **31**. The support **8** supports the speakers **1** through **4** so as to fulfill the following conditions (1) through (3).

Condition (1): The speakers **1** and **2** are located

forward with respect to a vertical plane represented by the chain line **400** in Figures **1A** and **1C**. The vertical plane represented by the chain line **400** is defined as a vertical plane which includes a straight line connecting the right ear hole and the left ear hole of the listener. The vertical plane represented by the chain line **400** will be referred to as the "vertical plane **400**" for convenience.

Condition (2): The speakers **3** and **4** are located rearward with respect to the vertical plane **400**.

Condition (3): The speakers **1** through **4** are located out of contact with the right and left ears of the listener.

The speaker supporting member **30** supports the speakers **1** and **3**, and the speaker supporting member **31** supports the speakers **2** and **4**. The speaker supporting members **30** and **31** are connected to each other by the headphone band **20**. The support **8** may have any other structure or shape as long as the support **8** supports the speakers **1** through **4** so as to fulfill the above conditions (1) through (3).

By the above-described location of the speakers **1** through **4**, the speakers **1** and **3** respectively have acoustically independent enclosures, and the speakers **2** and **4** also respectively have acoustically independent enclosures. Therefore, an acoustic signal from the speaker **1** and an acoustic signal from the speaker **3** independently reach the right ear of the listener along the shape of the head of the listener. Similarly, an acoustic signal from the speaker **2** and an acoustic signal from the speaker **4** independently reach the left ear of the listener along the

shape of the head of the listener. This means that information on the transfer function in front of and behind the individual listener is provided to the listener. As a result, the listener can correctly recognize a virtual sound source in front of or behind him/her regardless of the difference in different individuals' recognizing abilities.

Figure 2 shows a structure of a signal processing circuit **301a**. The signal processing circuit **301a** is one example of such a circuit usable in the headphone system **101**. The signal processing circuit **301a** outputs an acoustic signal to the speakers **1** and **2** for causing the listener to recognize a sound source in front of the listener.

In Figure **2**, reference numeral **50** represents a front center sound source indicated by the dotted line in front of the listener. The front center sound source **50** is not really present but is a virtual sound source which is recognized to be present by the listener. Hereinafter, the front center sound source **50** will be referred to as the "virtual sound source **50**".

The signal processing circuit **301a** receives, as input signals, a front right signal (FR signal), a front left signal (FL signal), a front center signal (FC signal), a rear right signal (SR signal), and a rear left signal (SL signal). The signal processing circuit **301a** processes these input signals to generate an acoustic signal, and outputs the acoustic signal to the headphone **201**.

The signal processing circuit **301a** includes filters **10a** and **11a**, and adders **12a** and **13a**.

The filter **10a** processes the FC signal. The adder **12a** adds the FC signal processed by the filter **10a** and the FR signal. The addition result is output to the speaker **1**.

The filter **11a** also processes the FC signal. The adder **13a** adds the FC signal processed by the filter **11a** and the FL signal. The addition result is output to the speaker **2**.

The SR signal is output to the speaker **3**, and the SL signal is output to the speaker **4**.

A transfer function X1 of the filter **10a** and a transfer function Y1 of the filter **11a** are designed to fulfill the following expressions (1) and (2). By thus designing the transfer functions X1 and Y1, the listener can correctly recognize the virtual sound source **50**.

$$h1 \cdot X1 + h3 \cdot Y1 = H1 \quad \text{..... expression (1)}$$

$$h2 \cdot X1 + h4 \cdot Y1 = H2 \quad \text{..... expression (2)}$$

Here, H1 is the transfer function from the virtual sound source **50** to the right ear hole of the listener, and H2 is the transfer function from the virtual sound source **50** to the left ear hole of the listener. Furthermore, h1 is the transfer function from the speaker **1** to the right ear hole of the listener, h2 is the transfer function from the speaker **1** to the left ear hole of the listener, h3 is the transfer function from the speaker **2** to the right ear hole of the listener, and h4 is the transfer function from the speaker **2** to the left ear hole of the listener.

From expressions (1) and (2), X1 is represented by expression (3) and Y1 is represented by expression (4).

$$X1 = (h4 \cdot H1 - h3 \cdot H2)/(h1 \cdot h4 - h2 \cdot h3) \ldots \text{expression (3)}$$

$$Y1 = (h1 \cdot H2 - h2 \cdot H1)/(h1 \cdot h4 - h2 \cdot h3) \ldots \text{expression (4)}$$

The transfer functions H1, H2, and h1 through h4 are measured with a specific listener. The specific listener may be an existent listener or a virtual listener.

In the case where a listener other than the specific listener (for example, listener A) uses the headphone **201** including the filters **10a** and **11a** designed based on the transfer functions H1, H2, and h1 through h4 measured with the specific listener, a transfer function H1' from the virtual sound source **50** to the right ear hole of the listener A is represented by expression (5).

$$\begin{aligned} H1' &= h1' \cdot X1 + h3' \cdot Y1 \\ &= h1' \cdot \{(h4 \cdot H1 - h3 \cdot H2)/(h1 \cdot h4 - h2 \cdot h3)\} \\ &\quad + h3' \cdot \{(h1 \cdot H2 - h2 \cdot H1)/(h1 \cdot h4 - h2 \cdot h3)\} \\ &= \{(h1' \cdot h4 - h2 \cdot h3') \cdot H1 \\ &\quad + (h1 \cdot h3' - h1' \cdot h3) \cdot H2\}/(h1 \cdot h4 - h2 \cdot h3) \\ &\qquad \ldots\ldots \text{expression (5)} \end{aligned}$$

Here, h1' is the transfer function from the speaker **1** to the right ear hole of the listener A, and h3' is the transfer function from the speaker **2** to the right ear hole of the listener A.

Based on expression (6), expression (5) is changed

to expression (7).

$$h1'\cdot h4-h2\cdot h3' >> h1\cdot h3'-h1'\cdot h3 \; \ldots\ldots \text{ expression } (6)$$

$$H1' \approx \{(h1'\cdot h4-h2\cdot h3')/(h1\cdot h4-h2\cdot h3)\}\cdot H1$$
$$= (1+\Delta h1)\cdot H1 \; \ldots\ldots \; (7)$$

Similarly, a transfer function H2' from the virtual sound source **50** to the left ear hole of the listener A is represented by expression (8).

$$H2' = (1+\Delta h2)\cdot H2 \; \ldots\ldots \text{ expression } (8)$$

$\Delta h1$ and $\Delta h2$ act as correction coefficients for correcting the individual difference of the listener A from the above-mentioned specific listener. In this manner, the headphone system **101** can allow any listener to recognize the virtual sound source **50** more correctly than conventional headphone systems which merely implement the transfer functions H1 and H2 (for example, the conventional headphone system shown in Figure **19**).

The above-described technique for correcting the individual difference among different listeners is used in common with all the examples described below.

Figure **3** shows a signal processing circuit **301b**. The signal processing circuit **301b** is another example of such a circuit usable in the headphone system **101**. The signal processing circuit **301b** outputs an acoustic signal to the speakers **3** and **4** for causing the listener to recognize the sound source behind the listener.

In Figure **3**, reference numeral **60** represents a rear sound source indicated by the dotted line behind the listener. The rear sound source **60** is not really present but is a virtual sound source which is recognized to be present by the listener. Hereinafter, the rear sound source **60** will be referred to as the "virtual sound source **60**".

The signal processing circuit **301b** receives, as input signals, a front right signal (FR signal), a front left signal (FL signal), a rear center signal (SC signal), a rear right signal (SR signal), and a rear left signal (SL signal). The signal processing circuit **301b** processes these input signals to generate an acoustic signal, and outputs the acoustic signal to the headphone **201**.

The signal processing circuit **301b** includes filters **10b** and **11b**, and adders **12b** and **13b**.

The filter **10b** processes the SC signal. The adder **12b** adds the SC signal processed by the filter **10b** and the SR signal. The addition result is output to the speaker **3**.

The filter **11b** also processes the SC signal. The adder **13b** adds the SC signal processed by the filter **11b** and the SL signal. The addition result is output to the speaker **4**.

The FR signal is output to the speaker **1**, and the FL signal is output to the speaker **2**.

A transfer function X2 of the filter **10b** and a transfer function Y2 of the filter **11b** are designed to fulfill the following expressions (9) and (10). By thus

designing the transfer functions X2 and Y2, the listener can correctly recognize the virtual sound source **60**.

$$h5 \cdot X2 + h7 \cdot Y2 = H3 \quad \ldots\ldots \text{ expression (9)}$$

$$h6 \cdot X2 + h8 \cdot Y2 = H4 \quad \ldots\ldots \text{ expression (10)}$$

Here, H3 is the transfer function from the virtual sound source **60** to the right ear hole of the listener, and H4 is the transfer function from the virtual sound source **60** to the left ear hole of the listener. Furthermore, h5 is the transfer function from the speaker **3** to the right ear hole of the listener, h6 is the transfer function from the speaker **3** to the left ear hole of the listener, h7 is the transfer function from the speaker **4** to the right ear hole of the listener, and h8 is the transfer function from the speaker **4** to the left ear hole of the listener.

From expressions (9) and (10), X2 is represented by expression (11) and Y2 is represented by expression (12).

$$X2 = (h8 \cdot H3 - h7 \cdot H4)/(h5 \cdot h8 - h6 \cdot h7) \quad .. \text{ expression (11)}$$

$$Y2 = (h5 \cdot H4 - h6 \cdot H3)/(h5 \cdot h8 - h6 \cdot h7) \quad .. \text{ expression (12)}$$

As described above, in the headphone system **101** according to the first example of the present invention, an acoustic signal for causing the listener to recognize the sound source in front of the listener is reproduced using the speakers **1** and **2** located forward with respect to the vertical plane **400** (Figures **1A** and **1C**), and the sound source behind the listener is reproduced using the speakers **3** and **4** located rearward with respect to the vertical plane **400**.

The information on the sound source in front of the listener is provided to the listener through the individual transfer functions which are set in accordance with the shape of the head of the listener in the direction from the sound source to the listener. The information on the sound source behind the listener is also provided to the listener through the individual transfer functions which are set in accordance with the shape of the head of the listener in the direction from the sound source to the listener. As a result, the listener can correctly recognize a sound source in front of or behind him/her regardless of the differences between different individuals' recognizing abilities.

The speakers **1** and **2** provided forward with respect to the vertical plane **400** (Figures **1A** and **1C**) are preferably located rearward with respect to a vertical plane represented by the chain line **401**. The vertical plane represented by the chain line **401** is defined as a plane which is parallel to the vertical plane **400** and includes a straight line connecting the right eye and the left eye of the listener. The vertical plane represented by the chain line **401** will be referred to as the "vertical plane **401**" for convenience. The above-described location of the speakers **1** and **2** prevents the speakers **1** and **2** from being in the field of vision of the listener. As a result, the listener can enjoy the video displayed on the large-scale screen without being disturbed by the speakers **1** and **2**.

(Example 2)

A headphone system **102** according to a second example of the present invention will be described with reference to Figures **4A** through **7**.

The headphone system **102** includes a headphone **202** (Figures **4A** through **4C**) and a signal processing circuit **302** (Figure **7**) for outputting an acoustic signal to the headphone **202**.

Figure **4A**, **4B** and **4C** show a structure of the headphone **202**. Figure **4A** is a top view, Figure **4B** is a front view, and Figure **4C** is a side view of the headphone **202**.

As shown in Figure **4A**, **4B** and **4C**, the headphone **202** includes right ear speakers **1** and **5**, left ear speakers **2** and **6**, and a support **8** for supporting the speakers **1**, **2**, **5** and **6**.

As in the first example, the support **8** supports the speakers **1**, **2**, **5** and **6** so as to fulfill the following conditions (1) through (3).

Condition (1): The speakers **1** and **2** are located forward with respect to the vertical plane **400**.

Condition (2): The speakers **5** and **6** are located rearward with respect to the vertical plane **400**.

Condition (3): The speakers **1**, **2**, **5** and **6** are located out of contact with the right and left ears of the listener.

According to the second example of the present invention, among acoustic signals for causing the listener to recognize a sound source located behind the listener, acoustic signals having a frequency of a prescribed

frequency fi or lower, are reproduced using the speakers **1** and **2** located forward with respect to the vertical plane **400**. Among the acoustic signals for causing the listener to recognize a sound source located behind the listener, acoustic signals having a frequency of a prescribed frequency fi or higher, are reproduced using the speakers **5** and **6** located rearward with respect to the vertical plane **400**. An acoustic signal having the prescribed frequency may be reproduced either using the speakers **1** and **2** or the speakers **5** and **6**.

The prescribed frequency fi is preferably defined as the upper limit of the frequency band in which there is substantially no difference between the transfer function from a sound source in front of the listener to the right (or left) ear of the listener (hereinafter, referred to as the "front transfer function") and the transfer function from a sound source behind the listener to the right (or left) ear of the listener (hereinafter, referred to as the "rear transfer function"). In other words, the differences between the transfer functions is almost zero.

Using such a system in which a part of the acoustic signals for causing the listener to recognize a sound source located behind the listener are reproduced using the speakers **1** and **2**, the speakers **5** and **6** can be reduced in size and weight.

In this system, the acoustic signals for causing the listener to recognize a sound source located in front of the listener are reproduced using the speakers **1** and **2** which are located forward with respect to the vertical plane **400**.

A difference between the front transfer function and the rear transfer function occurs because the shape of the head of the listener is asymmetric in the front-rear direction and the shape of the ears of the listener is asymmetric in the front-rear direction. However, the shape of the head and the shape of the ears are physically different in the front half and the rear half by merely a few centimeters or less.

The above-mentioned prescribed frequency fi can be specified in consideration of the relationship between the wavelength and the frequency of the acoustic signals. According to the second example, the prescribed frequency fi is set at, for example, about 1 kHz to about 3 kHz.

The difference in the size of the head or the ears among individuals is merely a few centimeters or less. Accordingly, the frequency at which the transfer functions starts to differ due to the individual difference almost matches the prescribed frequency fi.

Figure 5 is a graph illustrating one example of the front transfer function and the rear transfer function regarding a specific listener. The solid line represents an example of the head-related transfer function in the 0° direction (the direction straight ahead of the listener), and the dotted line represents an example of the head-related transfer function in the 180° direction (the direction directly behind the listener).

From the example shown in Figure 5, it will be appreciated that the front transfer function and the rear transfer function are largely different from each other in

the frequency band of about 1 kHz or more.

Figure **6** is a graph illustrating one example of the individual difference in the head-related transfer function in the 0° direction (the direction straight ahead of the listeners). The solid line represents an example of the head-related transfer function of listener A, the dotted line represents an example of the head-related transfer function of listener B, and the chain line represents an example of the head-related transfer function of listener C.

From the example shown in Figure **6**, it will be appreciated that the head-related transfer functions of the three listeners are also largely different from one another in the frequency band of about 1 kHz or more.

In the examples shown in Figures **5** and **6**, it is desirable to set the prescribed frequency fi at about 1 kHz. By reproducing the acoustic signals having the prescribed frequency fi or lower (in which there is substantially no difference in the head-related transfer function regardless of the direction or the listener) using the speakers **1** and **2**, the speakers **5** and **6** can have a smaller diaphragm and a more-lightweight magnetic circuit.

Figure **7** shows a structure of the signal processing circuit **302**. The signal processing circuit **302** outputs, among acoustic signals for causing the listener to recognize a sound source behind the listener, acoustic signals having a frequency of fi or lower to the speakers **1** and **2**. The signal processing circuit **302** outputs, among the acoustic signals for causing the listener to recognize a sound source behind

the listener, acoustic signals having the frequency of fi or higher to the speakers **5** and **6**.

In Figure **7**, identical elements previously discussed with respect to Figure **3** bear identical reference numerals and the descriptions thereof will be omitted.

The signal processing circuit **302** includes high pass filters (HPF) **141** and **142** for allowing signals having a frequency component of fi or higher, and low pass filters (LPF) **151** and **152** for allowing signals having the frequency component of fi or lower. The signal processing circuit **302** also includes the filters **110**, **111**, **10b**, **11b**, **210** and **211**, and adders **121** and **122**.

In Figure **7**, reference numerals **61** and **62** both represent virtual sound sources. In this example, the virtual sound source **61** is to the rear right of the listener, and the virtual sound source **62** is to the rear left of the listener.

The SR signal is input to the speaker **5** through the HPF **141**. The SR signal is also input to the LPF **151**. The output from the LPF **151** is input to the filters **110** and **111**.

The SL signal is input to the speaker **6** through the HPF **142**. The SL signal is also input to the LPF **152**. The output from the LPF **152** is input to the filters **210** and **211**.

The SC signal is input to the filters **10b** and **11b**.

The adder **121** adds the FR signal, the output from the filter **110**, the output from the filter **10b**, and the output

from the filter **210**. The addition result is output to the speaker **1**.

The adder **122** adds the FL signal, the output from the filter **111**, the output from the filter **11b**, and the output from the filter **211**. The addition result is output to the speaker **2**.

A transfer function X3 of the filter **110** and a transfer function Y3 of the filter **111** are designed to fulfill the following expressions (13) and (14). By thus designing the transfer functions X3 and Y3, the listener can correctly recognize the virtual sound source **61**.

$$X3 = (h4 \cdot H31 - h3 \cdot H41)/(h1 \cdot h4 - h2 \cdot h3)$$

.....expression (13)

$$Y3 = (h1 \cdot H41 - h2 \cdot H31)/(h1 \cdot h4 - h2 \cdot h3)$$

..... expression (14)

Here, H31 is the transfer function from the virtual sound source **61** to the right ear hole of the listener, and H41 is the transfer function from the virtual sound source **61** to the left ear hole of the listener.

A transfer function X4 of the filter **210** and a transfer function Y4 of the filter **211** are designed to fulfill expressions (15) and (16). By thus designing the transfer functions X4 and Y4, the listener can correctly recognize the virtual sound source **62**.

$$X4 = (h4 \cdot H32 - h3 \cdot H42)/(h1 \cdot h4 - h2 \cdot h3)$$

.....expression (15)

$$Y4 = (h1 \cdot H42 - h2 \cdot H32)/(h1 \cdot h4 - h2 \cdot h3) \quad \text{..... expression (16)}$$

Here, H32 is the transfer function from the virtual sound source **62** to the left ear hole of the listener, and H42 is the transfer function from the virtual sound source **62** to the right ear hole of the listener.

(Example 3)

A headphone system **103** according to a third example of the present invention will be described with reference to Figures **8A** through **9**.

Figure **9** shows a structure of the headphone system **103**. The headphone system **103** includes a headphone **203** and a signal processing circuit **303** for outputting an acoustic signal to the headphone **203**.

Figure **8A**, **8B** and **8C** show a structure of the headphone **203**. Figure **8A** is a top view, Figure **8B** is a front view, and Figure **8C** is a side view of the headphone **203**.

As shown in Figure **8A**, **8B** and **8C**, the headphone **203** includes right ear speakers **1** and **5**, left ear speakers **2** and **6**, and a support **8** for supporting the speakers **1**, **2**, **5** and **6**.

As according to the first example, the support **8** supports the speakers **1**, **2**, **5** and **6** so as to fulfill the following conditions (1) through (3).

Condition (1): The speakers **1** and **2** are located

forward with respect to the vertical plane **400**.

Condition (2): The speakers **5** and **6** are located rearward with respect to the vertical plane **400**.

Condition (3): The speakers **1**, **2**, **5** and **6** are located out of contact with the right and left ears of the listener.

According to the third example of the present invention, among acoustic signals for causing the listener to recognize a sound source located in front of the listener, acoustic signals having a frequency of the prescribed frequency fi or lower are reproduced using the speakers **5** and **6** located rearward with respect to the vertical plane **400**. Among the acoustic signals for causing the listener to recognize a sound source located in front of the listener, acoustic signals having a frequency of the prescribed frequency fi or higher are reproduced using the speakers **1** and **2** located forward with respect to the vertical plane **400**.

The prescribed frequency fi is set in a similar manner to that according to the second example.

By such a system in which a part of the acoustic signals for causing the listener to recognize the sound source located in front of the listener are reproduced using the speakers **5** and **6**, the speakers **1** and **2** can be reduced in size and weight.

In this system, the acoustic signals for causing the listener to recognize a sound source located behind the

listener are reproduced using the speakers **5** and **6** which are located rearward with respect to the vertical plane **400**.

Figure **9** shows a structure of the signal processing circuit **303**. The signal processing circuit **303** outputs, among acoustic signals for causing the listener to recognize a sound source located in front of the listener, acoustic signals having a frequency of fi or higher to the speakers **1** and **2**. The signal processing circuit **302** outputs, among the acoustic signals for causing the listener to recognize a sound source located in front of the listener, acoustic signals having a frequency of fi or lower to the speakers **5** and **6**.

In Figure **9**, identical elements previously discussed with respect to Figure **2** and **7** bear identical reference numerals and the descriptions thereof will be omitted. In Figure **9**, the virtual sound source **61** is to the front left of the listener, and the virtual sound source **62** is located to the front right of the listener.

The signal processing circuit **303** includes a high pass filters (HPF) **41** for allowing signals having a frequency component of fi or higher, and a low pass filter (LPF) **51** for allowing signals having the frequency component of fi or lower, in addition to the HPFs **141** and **142** and the LPFs **151** and **152**. The signal processing circuit **303** also includes the filters **110**, **111**, **10a**, **11a**, **210** and **211**, and adders **123**, **124**, **125** and **126**.

The FL signal is input to the HPF **141**. The output from the HPF **141** is input to the adder **125**. The FL signal is also input to the LPF **151**. The output from the LPF **151**

is input to the filters **110** and **111**.

The FR signal is input to the HPF **142**. The output from the HPF **142** is input to the adder **126**. The FL signal is also input to the LPF **152**. The output from the LPF **152** is input to the filters **210** and **211**.

The FC signal is input to the HPF **41** and the LPF **51**. The output from the HPF **41** is input to the filters **10a** and **11a**. The output from the HPF **51** is input to the adders **123** and **124**.

The adder **125** adds the output from the HPF **141** and the output from the filter **10a**, and outputs the addition result to the speaker **2**.

The adder **123** adds the SL signal, the output from the filter **110**, the output from the LPF **51**, and the output from the filter **210**; and outputs the addition result to the speaker **6**.

The adder **124** adds the output from the filter **111**, the output from the LPF **51**, the output from the filter **211**, and the SR signal; and outputs the addition result to the speaker **5**.

The adder **126** adds the output from the HPF **142** and the output from the filter **11a**, and outputs the addition result to the speaker **1**.

(Example 4)

A headphone system according to a fourth example of the present invention will be described with reference to

Figures **10A** through Figure **14B**.

The headphone system according to the fourth example includes a headphone **204** and a signal processing circuit (not shown) for outputting an acoustic signal to the headphone **204**.

As shown in Figures **10A**, **10B** and **10C**, the headphone **204** includes a low frequency-dedicated speaker **7** for only reproducing acoustic signals in a low frequency band, in addition to the elements described in the first through third examples.

In the first through third examples, the speakers are located out of contact with the ears of the listener. In this case, the reproduction level of the acoustic signals in the low frequency band is likely to be lowered. The low frequency-dedicated speaker **7** is provided for compensating for such a reduction in the reproduction level of the acoustic signals. Thus, acoustic signals in a wide frequency band can be satisfactorily reproduced by the headphone **204**.

In the low frequency band, the wavelength of acoustic signals is relatively long. Therefore, the front transfer function and the rear transfer function have almost no difference from each other. There is almost no individual difference in the transfer functions, either. Accordingly, the headphone **204** can have the low frequency-dedicated speaker **7** at various positions thereof.

Figures **10A**, **10B** and **10C** show an example of providing the low frequency-dedicated speaker **7** in the vicinity of

an upper rear part of the head of the listener. In this example, the headphone **204** includes a support assisting member **21** attached to the headphone band **20**. The support assisting member **21** supports the low frequency-dedicated speaker **7** so as to be located in the vicinity of the upper rear part of the head of the listener.

Figures **11A**, **11B** and **11C** show an example of providing the low frequency-dedicated speaker **7** in the vicinity of the top of the head of the listener. In this example, the low frequency-dedicated speaker **7** is directly attached to the headphone band **20** so as to be located in the vicinity of the top of the head of the listener.

Figures **12A**, **12B** and **12C** show an example of providing the low frequency-dedicated speaker **7** in the vicinity of a lower rear part of the head of the listener. In this example, the headphone **204** includes a support assisting member **22** which is attachable on the shoulders of the listener. The support assisting member **22** supports the low frequency-dedicated speaker **7** so as to be located in the vicinity of the lower rear part of the head of the listener.

In the example shown in Figures **10A**, **10B** and **10C**, it is more preferable that the contact area of the support assisting member **21** and the head of the listener is larger in order to stabilize the low frequency-dedicated speaker **7**.

Figures **13A** and **13B** show a support assisting member **21'** having an improved shape so as to increase the contact area with the head of the listener. Figures **14A** and **14B** show a support assisting member **21"** having another improved shape

so as to increase the contact area with the head of the listener.

The signal processing circuit is structured to output to the low frequency-dedicated speaker **7** a signal for reproducing only the acoustic signals in the low frequency band.

As described above, according to the fourth example, the reduction in the low frequency reproduction ability of the speakers which are located out of contact with the ears of the listener can be compensated for by providing a low frequency-dedicated speaker.

(Example 5)

A headphone system according to a fifth example of the present invention will be described with reference to Figures **15A**, **15B** and **15C**.

The headphone system according to the fifth example includes a headphone **205** and a signal processing circuit (not shown) for outputting an acoustic signal to the headphone **205**.

Figures **15A**, **15B** and **15C** are a top view, a front view and a side view of the headphone **205**.

As shown in Figures **15A**, **15B** and **15C**, the headphone system according to the fifth example includes vibration units **10** and **11** in addition to the elements of the headphones **201** through **203** described in the first through third examples. The vibration units **10** and **11** vibrate based on a dedicated low frequency band signal used for reproducing only the audio

signals in a low frequency band.

In the first through third examples, the speakers are located out of contact with the ears of the listener. In this case, the reproduction level of the acoustic signals in the low frequency band is likely to be lowered. The vibration units **10** and **11** are provided for compensating for such a reduction in the reproduction level of the acoustic signals. Thus, acoustic signals in a wide frequency band can be satisfactorily reproduced by the headphone **205**.

In the example shown in Figures **15A**, **15B** and **15C**, the vibration unit **10** is provided between the speaker supporting member **30** and one temporal region of the head of the listener, and the vibration unit **11** is provided between the speaker supporting member **31** and the other temporal region of the head of the listener.

The speaker supporting member **30** supports the speakers **1** and **5**. The speaker supporting member **31** supports the speakers **2** and **6**. The speaker supporting members **30** and **31** are connected to each other through a headphone band **20**.

The vibration units **10** and **11** are provided to be in close contact with the temporal regions of the head. The vibration of the vibration units **10** and **11** is conveyed to the bones of skull. As a result, bone conduction is generated. Thus, the listener can recognize the sound in the low frequency band.

The headphone **205** has another advantage that since the vibration units **10** and **11** are provided to be in close contact with the temporal regions of the head, the headphone

205 is unlikely to slip down from the head of the listener.

The signal processing circuit included in the headphone system according to the fifth example is structured to output a dedicated low frequency band signal to the vibration units **10** and **11**.

As described above, according to the fifth example, the reduction in the low frequency ability of the speakers which are located out of contact with the ears of the listener can be compensated for by providing the vibration units.

(Example 6)

A headphone system according to a sixth example of the present invention will be described with reference to Figures **16** and **17**.

The headphone system according to the sixth example includes a headphone **206** and a signal processing circuit (not shown) for outputting an acoustic signal to the headphone **206**.

The headphone **206** has the same structure as that of any of the headphones **201** through **205** described in the first through fifth examples.

According to the sixth example, the speakers **3** and **4** are located rearward with respect to the vertical plane **400** so that the angle made between a straight line **40**, which is in the straight ahead direction of the listener (i.e., perpendicular to the vertical plane **400**), and vertical lines **45** which, respectively, run through the centers of the front surfaces of the speakers **3** and **4** and are vertical to the

front surfaces of the speakers **3** and **4** is in the range of about 100 degrees and about 120 degrees.

By providing the speakers **3** and **4**, the listener can recognize the rear sound source in the range of about 100 degrees and about 120 degrees from the straight line **40**. This matches the standards BS.775 recommended by the International Telecommunication Union (ITU). Due to such a structure, the listener can recognize the rear sound source while sensing a preferable expansion of the sound.

In the example of Figure **16**, the speakers **3** and **4** are provided so that the angle made between the straight line **40** and the line running through the center of the front surface of the speakers **3** and **4** is about 110 degrees.

In Figure **16**, the line **41** makes an angle of about 110 degrees with the straight line **40** and runs through the center of the head of the listener. The line **42** makes an angle of about 110 degrees with the straight line **40** and runs through the left ear hole of the listener. The speaker **4** is provided so that the line running through the center of the front surface of the speaker **4** is parallel to the lines **41** and **42**.

The line **43** makes an angle of about 110 degrees with the straight line **40** and runs through the center of the head of the listener. The line **44** makes an angle of about 110 degrees with the straight line **40** and runs through the right ear hole of the listener. The speaker **3** is provided so that the line running through the center of the front surface of the speaker **3** is parallel to the lines **43** and **44**.

Figure **17** shows a headphone **206'** including an angle adjusting mechanism for adjusting the angle of the speakers **1** through **4** with respect to the listener.

In the example shown in Figure **17**, the headphone **206'** includes a speaker supporting member **30** for supporting the speakers **1** and **3**, and a speaker supporting member **31** for supporting the speakers **2** and **4**.

The speaker **1** and the speaker supporting member **30** are connected to each other through a hinge mechanism. Similarly, the speaker **3** and the speaker supporting member **30**, the speaker **2** and the speaker supporting member **31**, and the speaker **4** and the speaker supporting member **31** are connected to each other through a hinge mechanism. Namely, the speakers **1** through **4** are rotatably supported about the connecting portions.

By providing the angle adjusting mechanism shown in Figure **17**, the angle made between the straight head direction of the listener (the direction of the straight line **40** in Figure **16**) and the line running through the center of the front surface of each of the speakers **1** through **4** can be set to be in the above-described preferable range.

Such a mechanism also facilitates compensating for the undesirable deviation of the positions of the speakers and the ears of the listener due to the difference between different individuals.

The listener can select his/her favorite sound field perception by adjusting the angle made by the straight ahead direction of the listener and the lines running through the

centers of the front surfaces of the speakers **1** and **2** located forward with respect to the vertical plane **400**.

The speakers **1** and **2** may be fixed with respect to the listener while the speakers **3** and **4** are adjustable. Alternatively, the speakers **3** and **4** may be fixed with respect to the listener while the speakers **1** and **2** are adjustable.

As described above, according to the sixth example, the listener can recognize the sound field more accurately in multi-channel reproduction by setting in a prescribed range the angle made between the straight ahead direction of the listener and the lines running through the centers of the front surfaces of the speakers **3** and **4** which are located rearward with respect to the listener.

(Example 7)

A headphone system according to a seventh example of the present invention will be described with reference to Figures **18A**, **18B** and **18C**.

The headphone system according to the seventh example includes a headphone **207** and a signal processing circuit (not shown) for outputting an acoustic signal to the headphone **207**.

Figures **18A**, **18B** and **18C** are a top view, a front view and a side view of the headphone **207**.

As shown in Figures **18A**, **18B** and **18C**, the headphone **207** includes a reflection plate **510** for reflecting the sound radiating from the speaker **6**.

As shown in Figure **18A**, the speaker **6** is located so that the surface of the diaphragm of the speaker **6** includes a straight line **500** which connects the left ear hole of the listener and the center of the speaker **6**. The sound radiating from the speaker **6** is reflected by the reflection plate **510** and reaches the left ear of the listener.

By thus providing the speaker **6** and the reflection plate **510**, the sound transmitted forward with respect to the speaker **6** along the straight line **500** and the sound transmitted rearward with respect to the speaker **6** along the straight line **500** counteract each other and are reduced in amplitude on the straight line **500**. The sound, radiating from the speaker **6** in the straight ahead direction of the speaker **6** and reflected by the reflection plate **510**, reaches the left ear of the listener without being reduced. Therefore, the listener can recognize the sound as if the sound radiated from a virtual speaker **520**.

The rear surface of the speaker **6** is acoustically open.

Another reflecting plate may be provided for reflecting the sound radiating from the speaker **5**, and the speaker **5** may be positioned like the speaker **6**.

According to the seventh example, the listener can recognize the acoustic image of the virtual speaker which is relatively far from the head of the listener, using the speakers **5** and **6** located near the head of the listener. As a result, the headphone **207** can be reduced in size.

According to the present invention, a first speaker

and a second speaker are provided forward with respect to a vertical plane including the straight line connecting the right ear hole and the left ear hole of the listener, and a third speaker and a fourth speaker are provided rearward with respect to the vertical plane. The first through fourth speakers are located out of contact with the right and left ears of the listener.

By providing the first through fourth speakers in the above-described manner, an acoustic signal from the first speaker and an acoustic signal from the third speaker separately reach the right ear of the listener along the shape of his/her head. An acoustic signal from the second speaker and an acoustic signal from the fourth speaker separately reach the left ear of the listener along the shape of his/her head. This means that the information on the transfer function in front of and behind the individual listener is provided to the listener. As a result, the listener can correctly recognize a virtual sound source in front of or behind him/her regardless of the difference between the recognizing abilities of different individuals.

In one embodiment of the invention, among acoustic signals for causing the listener to recognize a sound source behind the listener, acoustic signals having a frequency of a prescribed frequency fi or lower are output to the first and second speakers, and acoustic signals having a frequency of the prescribed frequency fi or higher are output to the third and fourth speakers.

By reproducing a part of the acoustic signals for causing the listener to recognize a sound source behind the listener, using the first and second speakers in this manner,

the third and fourth speakers can be reduced in size and weight.

The first and second speakers are preferably located rearward with respect to a vertical plane including a straight line connecting the right eye and the left eye of the listener. By such an arrangement, the first and second speakers can be prevented from being in the field of vision of the listener. As a result, the listener can enjoy the video displayed on the large-scale screen without being disturbed by the first and second speakers.

Various other modifications will be apparent to and can be readily made by those skilled in the art without departing from the scope and spirit of this invention. Accordingly, it is not intended that the scope of the claims appended hereto be limited to the description as set forth herein, but rather that the claims be broadly construed.